TEMPORAL AND SPATIAL REPRESENTATIVENESS OF ALPINE SEDIMENT YIELDS: CASCADE MOUNTAINS, BRITISH COLUMBIA

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ABSTRACT

New alpine, lake-based sediment yield data are presented from a cirque basin in the alpine zone of the Cascade Mountains, British Columbia. Average rates of sediment deposition in Glacier Lake from a 1·33 km^2 basin were 7 t a^{-1}(BP) 10 300–6845 BP, 8 t a^{-1}(BP) 6845–3390 BP and 9·8 t a^{-1}(BP) 3390 BP to the present. The potential representativeness of the site is carefully assessed on the basis of three major axes of variability: lithology, climate and relief. Slope frequency data suggest the site is representative of the cirque component of the landscape but not of the whole alpine zone. The results emphasize the importance of considering the spatial variability of relief and the temporal variability of climate in assessing the representativeness of sediment yield data. ©1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

The use of modern process data to infer patterns of landscape evolution is hampered by the mismatch in both time and space scales between observations of process and major landscape change. Measured rates of sediment movement are both temporally and spatially specific. That is, they relate to the particular configurational state of a specific geomorphic system or part of a system. A common approach in extending site-specific data to larger-scale landscape issues is to compile larger-scale datasets from published sources. As Hicks *et al*. (1990) have noted, paucity of data has meant that such compilations are frequently marked by a lack of attention to the representativeness of the data. No single measurement can be truly representative of changing process rates in a complex system, yet the difficulty and expense involved may preclude intensive sampling. The need to provide a process base for work on landscape evolution therefore requires that geomorphologists attempt to identify study sites that are ‘typical’ with regard to major controls on the process studied. This necessitates careful attention to defining the system of interest.

The intense climate and available potential energy in alpine landscapes make them zones of potentially high geomorphic activity. It is therefore important that they are adequately characterized in any considerations of landscape evolution. However, the availability of sediment yield data from unglacierized alpine (above the treeline) basins is very limited. This paper presents some new results from a study of Holocene sediment movement in the Cascade Mountains of British Columbia.

Lithology, relief and climate are major controls on sediment yield. They represent three possible axes of variability, both spatial and temporal, in sediment yields from a region. The importance of lithology as a control on weathering and sediment production is widely recognized. Similarly, there is a long history of regionalizing sediment yield data on the basis of climate (e.g. Langbein and Schumm, 1958; Walling and Kleo, 1979). Modelling experiments are starting to indicate effects of the long-term evolution of relief on sediment transport (Koons, 1989). Less attention has been paid to assessing temporal representativeness with respect to climate and spatial representativeness in terms of relief. Therefore, in this study of sedimentation in an alpine lake,

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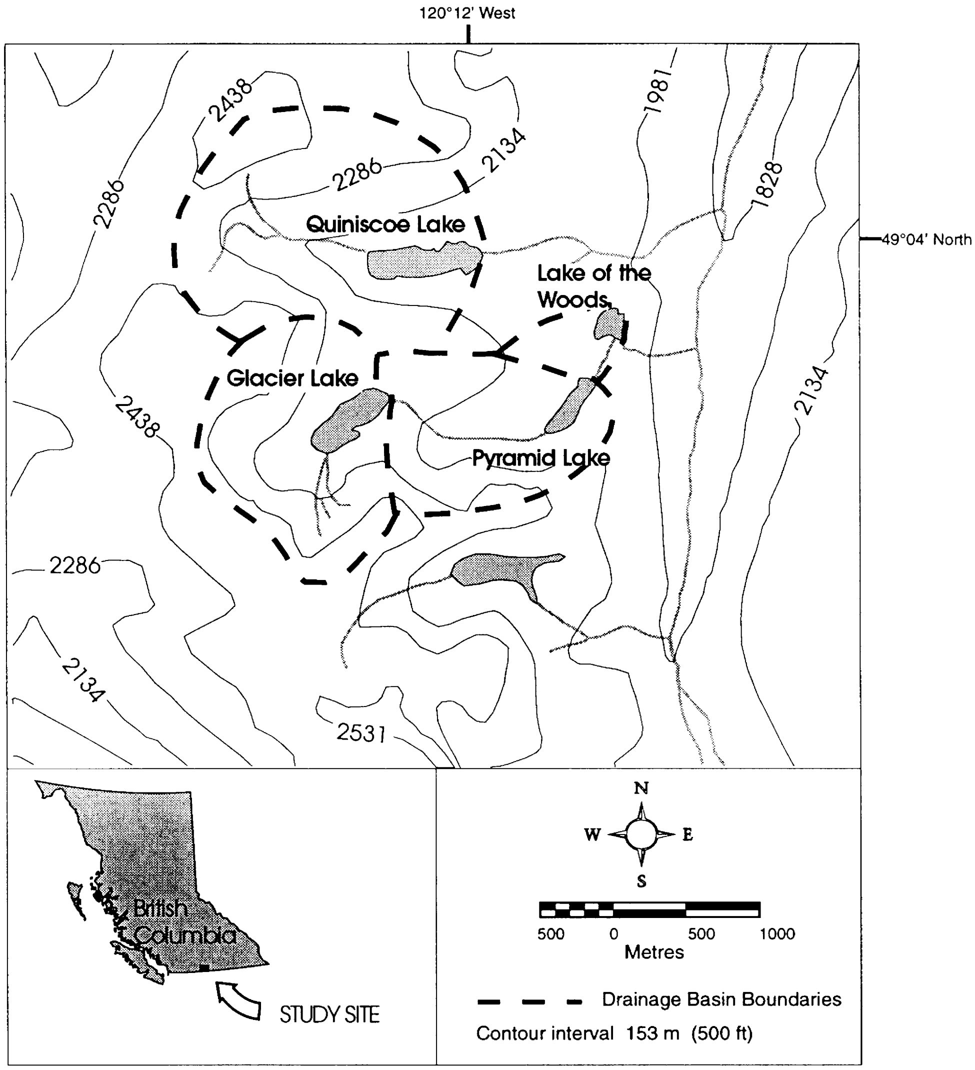

Figure 1. Location of the Glacier Lake Basin.

particular attention is given to establishing the spatial limits of the geomorphic system in question, the temporal representativeness of the sediment yield data, and hence the potential generalizability of the results.

STUDY SITE

Cathedral Provincial Park lies in the Okanagan Range of the Cascade Mountains, British Columbia. The lake sedimentation data presented here are from Glacier Lake in the centre of the park (elevation 2200 m a.s.l., catchment area 1·33 km^2, lake area 0·086 km^2) (Figure 1). The lake lies at the treeline and is surrounded by grasses, shrub tundra, and patches of *Larix lyallii* and *Abies lasiocarpa*. There is no evidence of Holocene glaciation in the basin. In the following, the regional representativeness of the glacier lake site is assessed for each of the axes of variability identified above.

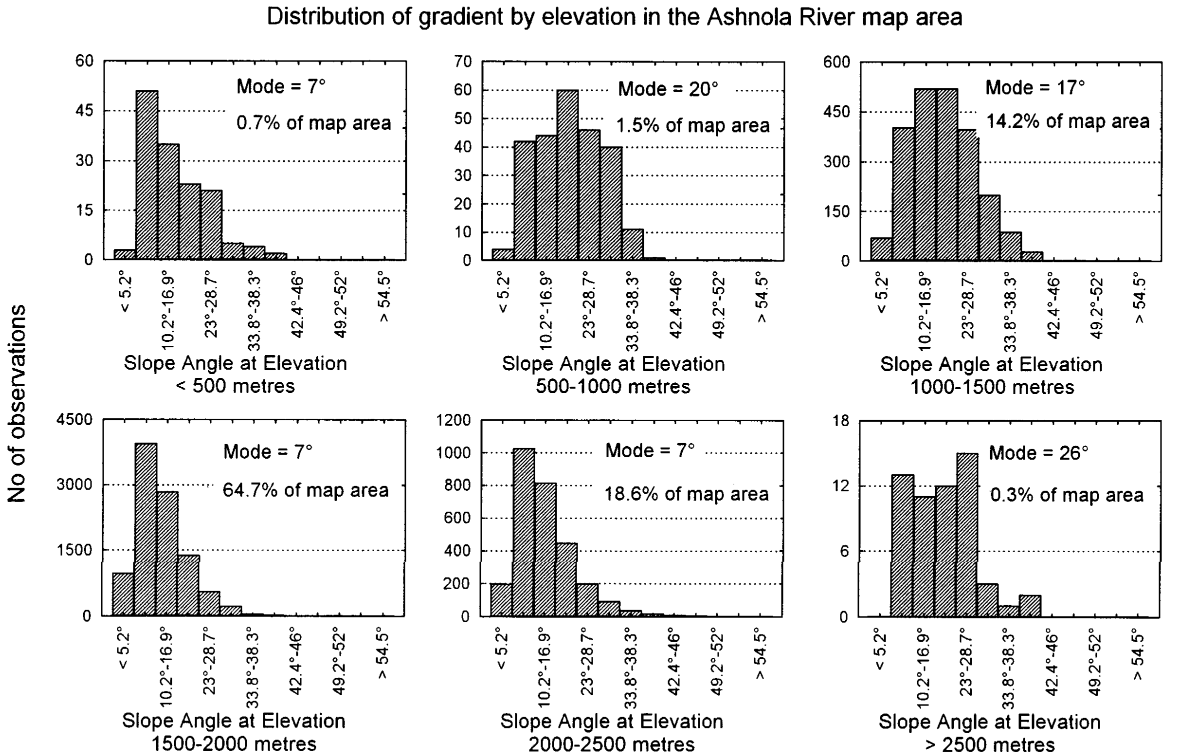

Figure 2. Slope frequencies in the Cathedral Park map area. Note that class sizes on the *x*-axes are uneven owing to the sampling method.

Lithology

The Okanagan ranges lie on the border between two geologic provinces (Melcon, 1973). To the south, the North Cascade range is composed predominantly of sedimentary and metamorphic rocks (McKee, 1972), whilst to the north the Interior Plateau of British Columbia is underlain primarily by volcanic rocks. The geology of the Glacier Lake basin reflects the transitional nature of the Okanagan ranges. The lake is underlain by granodiorite, whilst the upper slopes and cirque headwall are composed of Miocene basalts and sandstones of the Princeton group, and Triassic andesites of the Nicola group (Rice, 1947).

Climate

The Glacier Lake basin lies in the dry interior of British Columbia. To the west, moisture increases along a steep gradient to the coast. No measured climate data are available from the site. However, it is snow-free from July until September and comparison with other mountain climate data from the southern interior suggests that annual precipitation is *c.* 700 mm and mean annual temperature is close to 0°C. The basin would therefore be classified as a dry interior (Rocky) mountain site by Slaymaker (1990). The site may be regarded as climatically typical of the mountains of the Southern Interior, lying as it does on the border of the tundra and Engelmann spruce–subalpine fir biogeoclimatic zones (Meidinger and Pojar, 1991).

Relief

General physiography. To the south of the study site, Pliocene uplift and Pleistocene glaciation have combined to produce an area of high relief and rugged topography. To the north, the landscapes of the interior plateau present a more subdued relief. The Cathedral Lakes area again is intermediate between these two provinces, with deep valleys and cirque basins cut into a high upland surface.

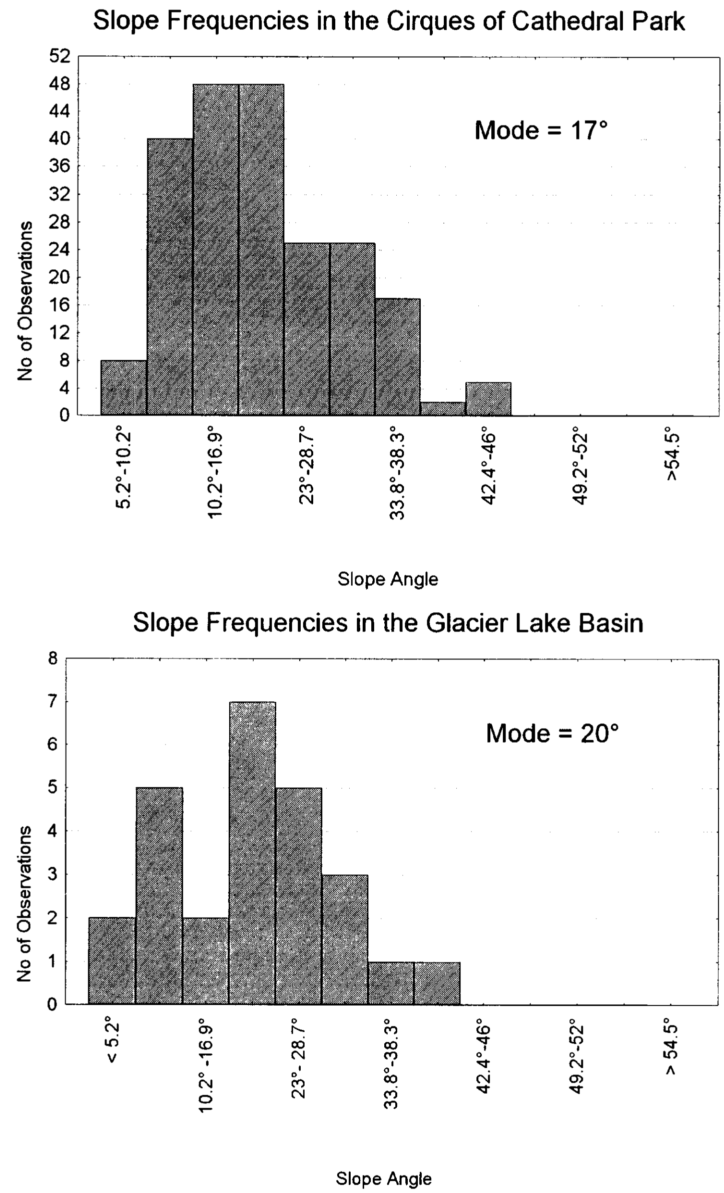

Figure 3. Cirque slope frequency distributions from Cathedral Park and, for comparison, the slope frequency distribution of the Glacier Lake basin.

Variable morphology of the alpine zone. Caine (1974) noted the relatively minor role played by fluvial processes in the alpine zone. In such a system, where slope processes dominate, the importance of relief as a control on sediment yield is emphasized. The alpine zone is traditionally defined ecologically, not geomorphologically, and may therefore exhibit a range of morphologies (Barsch and Caine, 1984). Spatial variability in sediment yield controlled by varying relief should therefore be expected. Three main morphological units appear to dominate the alpine landscape of Cathedral Park. These are cirque basins (*c.* 20 per cent of area), high plateaux (*c.* 20 per cent of area), and straight slopes crossing the treeline (≤ 60 per cent of area). Slope frequency distributions compared with regional data demonstrate the distinctiveness of the cirque landscape component of the alpine system. Figure 2 is a series of slope frequency distributions derived from the

972 km^2 map area including Cathedral Park (NTS 92/H1). The slope values were estimated by counting the number of 100 ft contour lines in each of a grid of 250 m circles superimposed on the map. The steep slopes identified in the distributions for elevations at intervals of 500–1000 m and 1000–1500 m (mode 20° and 17°) represent the sides of incised river valleys. The slope frequency distributions for the 1500–2500 m elevation band are negatively skewed with a mode at 7°. From 1500 to 2000 m these lower angled slopes are the floors of subsidiary river valleys. In the alpine zone, above 2000 m, the low-angled slopes are largely broad flat interfluves.

Figure 3 presents slope frequency distributions aggregated for all cirques (13) in Cathedral Park, as well as for the Glacier Lake cirque alone. These distributions have modes of 17° and 20° respectively. The steepness of these basins in comparison with the whole alpine zone is a function of the removal of the flat interfluves and the increased dominance of the cirque headwall. A chi-squared test rejects at the 0·001 level the hypothesis that the data from the cirques and from the whole alpine zone are drawn from a common population. The sample size of the Glacier Lake cirque data is too small to allow chi-square comparison with the general cirque data. However, the similarity of mean and standard deviation between the two data sets (Glacier Lake: mean 19·6, standard deviation 10·4; cirques: mean 19·7, standard deviation 10·3) suggests that the Glacier Lake basin is representative of the larger cirque system. A Kolmogorov–Smirnov test supports this view, showing no significant difference between the two distributions at the 0·05 level.

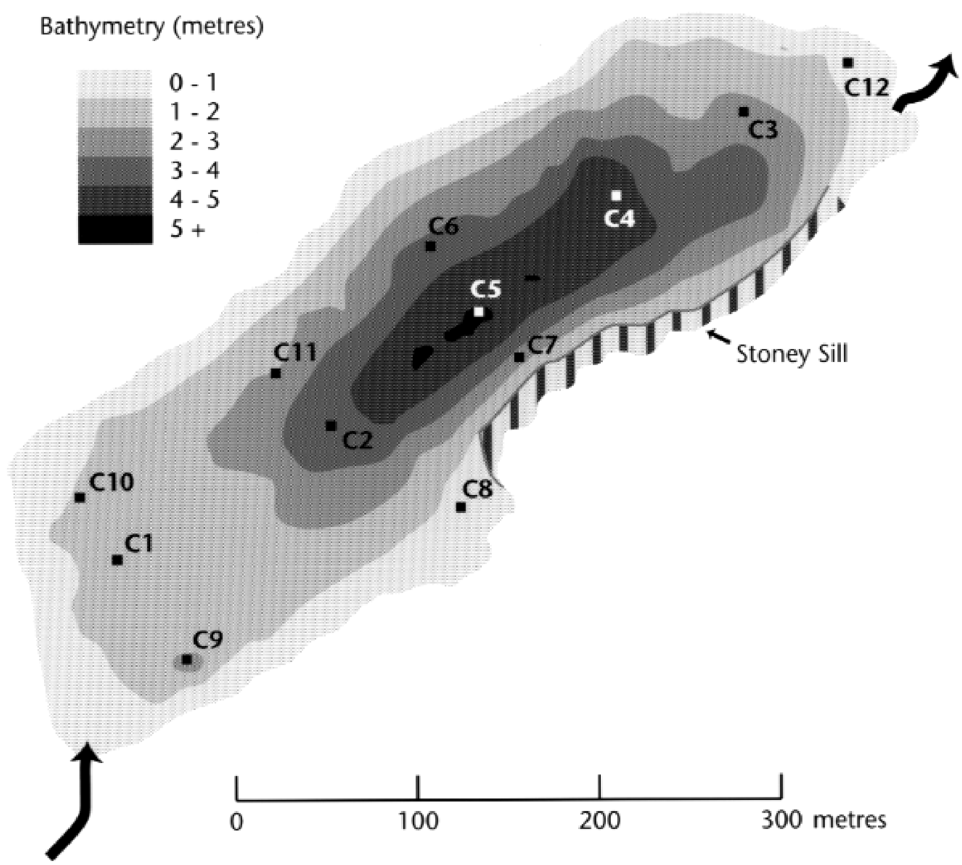

Figure 4. Core locations and the bathymetry of Glacier Lake.

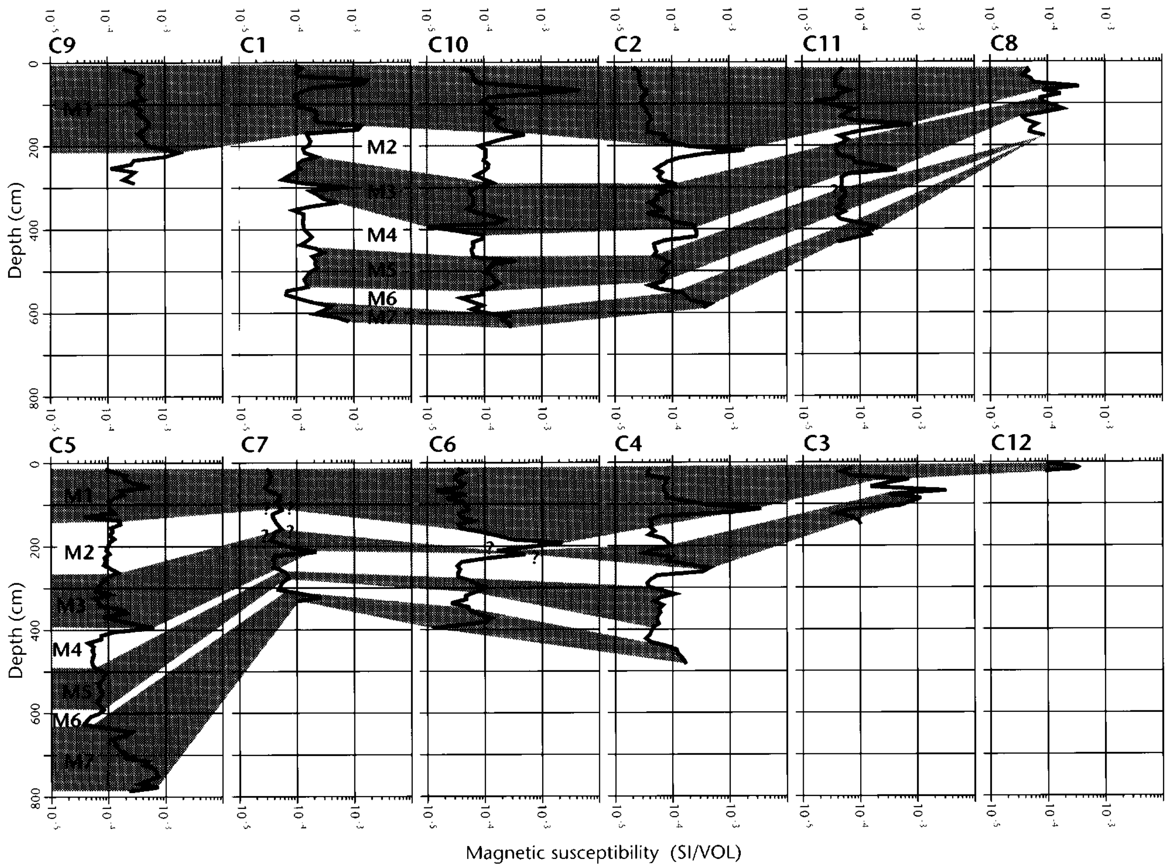

Figure 5. Magnetic susceptibility traces for the 12 cores showing correlation points. Correlations are based on visual and X-ray stratigraphy as well as the magnetic data.

The results suggest that slope frequencies in the Glacier Lake basin are representative of the cirque component of the alpine zone in Cathedral Park. These cirque basins appear to comprise a distinct component of the alpine landscape in the region. Results from Glacier Lake should not therefore be regarded as representative of the alpine zone as a whole, but may be interpreted more narrowly as representing the sediment yield of an alpine cirque basin.

HOLOCENE SEDIMENT YIELDS TO GLACIER LAKE

Holocene patterns of sedimentation in Glacier Lake have been reconstructed based on 12 lake sediment cores (Figure 4). Correlation of the cores based on magnetic susceptibility measurements supplemented by visual and X-ray stratigraphy allowed the recognition of seven stratigraphic zones (Figure 5). Core sedimentation rates were apportioned across the area of the lake by Voronoi tesselation between the core sites. Sediment volumes calculated for each polygon were converted to mass using measured bulk densities and corrected for measured sediment concentrations of carbonate, organic matter and autochthonous silica (Table I). Measured modern aeolian deposition to the lake is less than 1 per cent of annual sediment accumulation and is disregarded. No correction has been made for lake trap efficiency. Therefore the data are strictly a record of lake sedimentation. However, the morphology of the Glacier Lake basin suggests a high trap efficiency. The data may therefore be regarded as a reasonable minimum estimate of sediment yield to the lake.

Table I. Glacier Lake sedimentation data

Zone	Sedimentation (t)*	Diatom silica concentration (%)†	Carbonate concentration (%)‡	Organic matter concentration (%)§	Dry mass/wet volume ($kg m^{-3}$)¶
1	33415	2·22	2·04	13·48	333·6
2	12001	2·55	2·05	12·59	300·1
3	15672	2·44	1·75	11·69	341·7
4	9039	7·06	2·82	16·78	253·8
5	15089	9·99	2·79	13·80	307·6
6	4727	9·59	3·06	17·11	311·0
7	17142	3·19	2·10	7·58	456·3

* Calculated as the sum of sediment mass calculated for each zone and each polygon corrected by measured concentrations of carbonate and organic matter for each core. The sum was then corrected on the basis of the measured concentration of diatom silica from core c5.
† NaOH-soluble fraction measured at 50 cm intervals for core C5. Extrapolation of this value to all cores is a possible unquantified source of error.
‡ Mass loss at 925°C for 4 h. This was measured on integrated samples along the length of all 12 cores. The figures presented here are a weighted average.
§ Mass loss at 550°C for 1 h. Measured and presented in the same manner as the carbonate data.
¶ Measured on intergrated samples along each core. Average values presented here.

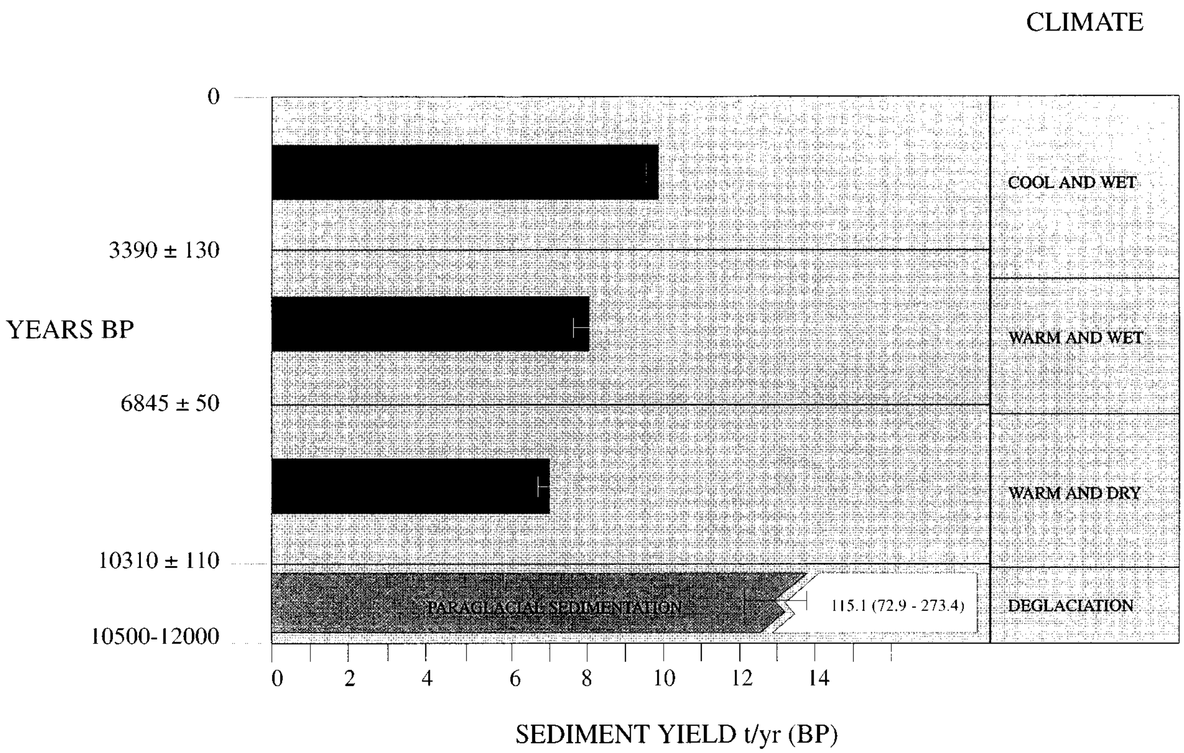

Figure 6. Holocene sediment yield to Glacier Lake. Error bars on the sedimentation estimates are calculated based on the error terms of the ^{14}C dates. The grey and white on the lower bar represent minimum/maximum estimates. The bracketed dates are an approximation based on the absence of the Glacier Peak tephra from the basin (dated at 12 750 ± 350 BP (Porter, 1978)) and on regional patterns of deglaciation as described by Clague (1981). Note that sediment yield is expressed in tonnes per radiocarbon year and may vary by *c.* 10 per cent from calendar year calculations.

Dating control on the sediment sequence is provided by two tephra, Mazama, an important regional marker in British Columbia, dated to 6845±50 BP (Bacon, 1983), and St Helens Yn, 3390±130 BP (Fulton, 1971); and a bulk radiocarbon date of 10 310±110 BP (Beta 87710). Figure 6 presents Holocene sediment yields to Glacier Lake based on this dating control, and estimates of the minimum/maximum likely dates of deglaciation. After the high paraglacial sedimentation rates (between 12·9 (12·1–13·8) and 115·1 (72·9–273·4) $t\,a^{-1}$(BP)), there is a trend of increasing long-term average sediment yields throughout the Holocene (7 ± 0·3 $t\,a^{-1}$(BP) from 10 310 to 6845 BP, 8 ± 0·4 $t\,a^{-1}$(BP) 6845–3390 BP). (The notation $t\,a^{-1}$(BP) is used to indicate that the time units are radiocarbon years.) The most marked increase has been since 3390 BP to values of 9·8 (9·5–10·2) $t\,a^{-1}$(BP). Also marked on Figure 6 is a summary of the pattern of Holocene climatic change in southern British Columbia. The summary is based on the comprehensive review of palaeoecological studies of palaeoclimate in the region provided by Hebda (1995). The increase in sediment yield is mirrored by a wettening trend with cooler conditions subsequent to 4000 BP. In the Coast Mountains this period was marked by two periods of Neoglaciation (3300–1900 BP and 900–100 BP (Ryder and Thomson, 1986)). There is no evidence for renewed glacial activity in the glacier basin. However, the pattern of increased sediment yields to the lake suggests a possible link between increased subaerial erosion and wetter, and particularly cooler, conditions through the Holocene.

The late Holocene sediment yield estimates for the site are one to three orders of magnitude greater than those reported in the Coast Mountains by Owens and Slaymaker (1992) and Souch and Slaymaker (1986). The basin, however, is one to two orders of magnitude larger than those in the cited studies. This is consistent with the scale control of sediment yield associated with the reworking of paraglacial material reported for British Columbia by Church and Slaymaker (1989).

CONCLUSIONS

The Glacier Lake basin appears to be a typical alpine cirque basin in the dry interior of Southern British Columbia. However, sediment yield to Glacier Lake cannot be regarded as representative of the entire alpine zone in the area, but only of the cirque component of the landscape. Reconstructions of sedimentation patterns in the lake suggest variability of Holocene sediment yields which correlates with the trend in Holocene climate. These findings emphasize the importance of spatial variability of relief and temporal variability of climate as controls on sediment yield. Large-scale data compilations offer the prospect of identifying large-scale controls on alpine sediment yield, and may also provide the basis for calibration of models of landscape evolution. However, the credibility of such efforts will depend on the demonstrated representativeness of the data.

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